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Our research plan had three parts: First, we needed to develop a task battery. This goal has been accomplished; many iterations were required to equate the tasks for difficulty. In fact, the task battery (including a paper-and-pencil version) was modified in response to feedback from Air Force researchers S. Chaiken and P. Kyllonen. Second, we wanted to validate the battery using positron emission tomography (PET). This testing and the preliminary analyses are complete. As expected, the tasks do in fact activate at least sotne distinct brain areas. However, of greater interest is the question of whether individual differences in activation of different areas predicts performance in different tasks. Those analyses are still underway. Finally, the original plan was to use the battery to illuminate the nature of performance in real-world tasks. The period of the grant was reduced, and we have not had time to pursue this line of research. We hope to be able to do so in a subsequent project.

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FINAL REPORT:
Individual Differences in Visual Cognition
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S. M. Kosslyn, P. I.

The present work grew out of that reported by Dror, Kosslyn & Waag (1993), who found that Air Force pilots judged metric spatial relations and rotated objects in mental images better than non-pilots, but they did not judge categorical spatial relations, extrapolate motion, scan images, or extract visual features from objects obscured by visual noise better than non-pilots. One goal of the present research was to develop an instrument that will allow one to predict whether a given person will perform well in a wide range of tasks that require visual cognition.

Our research plan had three parts: First, we needed to develop a task battery. This goal has been accomplished; many iterations were required to equate the tasks for difficulty. In fact, the task battery (including a paper-and-pencil version) was modified in response to feedback from Air Force researchers S. Chaiken and P. Kyllonen. Second, we wanted to validate the battery using positron emission tomography (PET). This testing and the preliminary analyses are complete. As expected, the tasks do in fact activate at least some distinct brain areas. However, of greater interest is the question of whether individual differences in activation of different areas predicts performance in different tasks. Those analyses are still underway. Finally, the original plan was to use the battery to illuminate the nature of performance in real-world tasks. The period of the grant was reduced, and we have not had time to pursue this line of research. We hope to be able to do so in a subsequent project.

In addition to these goals, we sought to conduct basic research that would directly bear on our theories of individual differences. We have done so, and the results of these studies have led us to refine our theories (as described in detail in our proposed renewal). Specifically, this grant has supported the following work.

1. Four component processes of imagery: PET study

We have tested 16 subjects in a study designed to discover whether there are different, independent components of visual mental imagery, specifically: composition (amalgamating parts into a single imaged object), inspection (seeking specific shapes in images), resolution (visualizing with high acuity) and transformation (specifically, mental rotation). We have also obtained a measure of fluid intelligence, the Raven Progressive Matrices, in order to remove the

influence of general intelligence per se. We not only predict (and have found) that different individuals will have varying abilities on each of these aspects of imagery, but also predict that variation in performance of the four processes will be related to variation in activation of the different brain areas.

During the PET session, each subject was tested twice on each of these four dimensions of imagery. We have compared activation in each task to each other task (using ANOVA contrasts on the PET scanning data). We are now in the process of examining the behavioral data (response times and error rates) and performing multiple regression analyses in which we discover in which brain areas individual differences in blood flow are correlated with differences in task performance. Regions will be drawn at a 5-mm radius around each of the maximally activated voxels in a given contrast. A program specially prepared for this analysis will extract the average values for each ROI (normalized relative to the global mean for the whole brain). These numbers will then be entered into a regression analysis with the response times and error rates from each subject; scores on the Raven Progressive Matrices test will be forced in initially, to remove the contribution of g.

2. Four component processes of imagery: fMRI study

We wish to discover whether we obtain comparable results with PET and fMRI, and thus have tested 20 subjects on an event-related fMRI study in which the stimuli, order and counterbalancing variables are identical to the PET study. As in the PET study, response times and error rates have been collected for each subject, as well as scores on the Raven Progressive Matrices test. The data will be analyzed using a regression design. This study will also permit us to compare results between the two neuroimaging techniques and will help us to answer questions about the feasibility of individual differences analyses using fMRI, a controversial topic at present. The data analyses are underway. To obtain a final group of 16 subjects who present usable data (free of motion artifacts), we estimate that we will require initial data collection from 25 subjects.

3. Kosslyn, S. M., Thompson, W. L., Wraga, M. and Alpert, N. M. (under review). Imagining rotation by endogenous and exogenous forces: Distinct neural mechanisms for different strategies. *NeuroReport*

One of the four imagery abilities we want to assess across individuals is image transformation ability. We have implemented this with an image rotation test, but wanted to understand this process better; it is likely that there is more than one way in which images can be rotated, and some people may find one versus another method easier. Previous neuroimaging studies of mental image transformations have sometimes implicated motor processes and sometimes not. In this study, prior to neuroimaging the subjects either viewed an electric motor rotating an angular Shepard-Metzler multi-armed object, or they rotated the object manually. Following this, they performed the

identical mental rotation task in which they compared members of pairs of such figures, but were asked to imagine the figures rotating as they had just seen the model rotate. When results from the two rotation conditions are directly compared, motor cortex (including Area M1) was found to be activated only when subjects imagined the rotations as a consequence of manual activity. Thus, there are at least two, qualitatively distinct, ways to imagine objects rotating, and these different strategies can be adopted voluntarily.

4. Wraga, M. Kosslyn, S. M., Thompson, W. L. and Alpert, N. M. (in preparation). PET investigation of strategy carry-over effects in mental rotation.

In this study, we examined whether a shift in mental rotation strategy (for one type of object, in this case the Shepard-Metzler figures used in the study described above) could be induced by asking subjects first to perform a task that typically requires a different strategy for mental rotation. Thus, eight subjects first performed a task in which they were asked to mentally rotate drawings of human hands (which has been shown to activate motor areas), and then were asked to mentally rotate Shepard-Metzler figures (which typically produces parietal activation, but no motor activation). This Shepard-Metzler figure rotation was compared with the same task in eight other subjects who were never asked to mentally rotate the hand drawings, but instead were always asked, in each condition, to mentally rotate Shepard-Metzler figures. We expected that having been exposed to the hand-rotation task initially would set a motor-based mental rotation strategy that would be carried over to Shepard-Metzler rotation. Data analysis has now been completed for this project, and the report is being written for submission. Motor areas, typically involved with imagined rotation of the hands, were implicated in rotation of Shepard-Metzler figures when this condition followed hand rotation, but not otherwise. This study addresses the larger issue of there being more than one mental strategy to accomplish the same mental task and opens onto the idea of individual differences.

5. Ganis, G., Keenan, J. P., Kosslyn, S. M. and Pascual-Leone, A. (2000). Transcranial magnetic stimulation of primary motor cortex affects mental rotation" *Cerebral Cortex, 10,* 175-180.

Neuroimaging studies have shown that motor structures are activated not only during overt motor behavior but also during tasks that require no overt motor behavior, such as motor imagery and mental rotation. We tested the hypothesis that activation of the primary motor cortex is needed for mental rotation by using single pulse transcranial magnetic stimulation (TMS). Single pulse TMS was delivered to the representation of the hand in left primary motor cortex while subjects performed mental rotation of pictures of hands and feet. Relative to a peripheral magnetic stimulation control condition, response times (RTs) were slower when TMS was

delivered at 650 ms but not at 400 ms after stimulus onset. The magnetic stimulation effect at 650 ms was larger for hands than for feet. These findings demonstrate that (1) activation of the left primary motor cortex has a causal role in the mental rotation of pictures of hands; (2) this role is stimulus-specific because disruption of neural activity in the hand area slowed RTs for pictures of hands more than feet; and, (3) left primary motor cortex is involved in the mental rotation process relatively late.

6. Kosslyn, S. M., Sukel, K. E. and Bly, B. M. Squinting with the mind's eye: Effects of stimulus resolution on imaginal and perceptual comparisons. (1999). *Memory and Cognition* 27 (2), 276-287.

Another of our four imagery tests focuses on image acuity. We wanted to develop objective tasks to assess this variable. Subjects either viewed or visualized arrays that were divided into four quadrants, with each quadrant containing a set of stripes. In two experiments, one array contained only relatively narrow (high-resolution) stripes, and one contained only relatively thick (low-resolution) stripes. Subjects compared sets of stripes in different quadrants according to their length, spacing, orientation, or width. When subjects visualized the arrays, they required much more time to compare high-resolution patterns than low-resolution patterns; when subjects saw the arrays, they evaluated both types of arrays equally easily. In addition, the relative ease of making the different discriminations was comparable in imagery and perception. Results from a third experiment provide strong evidence that people use imagery in this task; in one condition subjects evaluated oblique sets of stripes and in another condition evaluated vertical and horizontal stripes. In both imagery and perception, subjects made more errors when evaluating oblique stimuli, and in imagery they also required more time to evaluate oblique stimuli. The results suggest that additional effort is required in imagery to represent visual patterns with high resolution. This finding demonstrates that although imagery and perception may activate common brain regions, it is more difficult to represent high-resolution information in imagery than in perception.

7. Thompson, W. L., Kosslyn, S. M., Sukel, K. E. and Alpert, N. M. (in press). Mental imagery of high- and low-resolution gratings activates Area 17. *NeuroImage.*

We conjectured that very high resolution imagery would rely on visual parts of the brain that have the highest resolution. However, only some previous neuroimaging studies of visual mental imagery have found that Area 17 (primary visual cortex) is activated when people visualize objects. The present study was designed to test the hypothesis that the necessary degree of resolution of the mental image is a determining factor in whether Area 17 is activated during imagery. Eight male subjects visualized and compared sets of stripes that required high or low resolution to resolve while their brains were scanned using $^{15}O_{CO2}$ positron emission tomography (PET). When imagery in general

(visualization of high- and low-resolution gratings stimuli combined) was compared to an auditory baseline condition where subjects did not visualize, Area 17 was activated. However, region of interest (ROI) and statistical parametric mapping (SPM) analyses revealed no difference between imagery conditions using high- and low-resolution stimuli. These results indicate that the resolution of the stimuli alone does not necessarily determine whether Area 17 will be activated during visual mental imagery.

8. Gratings replication with Transcranial Magnetic Stimulation (TMS)

We have begun testing subjects on a study that is a follow-up to the one published in Science in 1999. In this study, we ask subjects to learn the appearance of a rectangle divided into quadrants. Each quadrant contains a set of gratings (a series of stripes). The gratings in each quadrant vary along four dimensions: length of the bars making up the stripes, width of the bars, spacing between the bars and tilt (orientation of the bars away from the vertical). During the experimental phase, subjects are asked on each trial to compare two of the four possible gratings on one of the four dimensions. The cues are delivered aurally. For example, if the subjects hear "1, 3, length," they are to decide whether the bars in Quadrant 1 are longer than the bars in Quadrant 3. If the judgment is "yes", the subjects press one key and if the judgment is "no", they press the other key. Across subjects, all the quadrants will be compared to each other on all four dimensions. There are three conditions of interest: 1 Hz TMS (where the TMS pulse sequence is delivered over the brain region hypothesized to be affected at a rate of one pulse per second); 20 Hz TMS (where the sequence is delivered over the same location at 20 pulses per second) and "sham" TMS (where the TMS coil is positioned slightly differently so that the magnetic stimulation does not enter the brain, but the sound of the coil and the feel of it on the scalp make this condition indistinguishable from those using real TMS).
We hypothesize that compared to sham TMS, the 1 Hz sequence will hinder performance on the imagery task described above (based on previous results, e.g. Kosslyn et al., 1999), while the 20 Hz condition may facilitate performance based on preliminary findings.

9. Thompson, W. L. & Kosslyn, S. M. 2000. Neural systems activated during visual mental imagery: A review and meta-analyses. In A. W. Toga & J. C. Mazziotta (Eds.), *Brain mapping: The systems.* (pp. 535-560). San Diego, CA: Academic Press.

Our studies led us to the view that there not only are distinct processes used in imagery (which is what our current task battery assesses), but there may be distinct types of visual/spatial imagery. This review study examines the variables that contribute to the neural activation (as measured by neuroimaging techniques) of a subset of regions posited to be involved in implementing visual mental imagery. Based on a theory of imagery, we proposed eleven factors that

could explain some of the variance in the results of neuroimaging studies of mental imagery. We coded each of the studies according to each of the independent variables. The dependent variables were binary codes that indicated whether activation was present in three regions: medial occipital cortex, posterior parietal cortex, and inferior/middle temporal cortex. Three forward stepwise regression analyses were performed (one per dependent variable), which revealed that the resolution of the image, among other variables, predicted activation in medial occipital cortex. Different variables predicted activation in posterior parietal and inferior/middle temporal activation. This meta-analysis demonstrated that variations in results are not random, and that different factors govern the activation of different neural structures. In current work (summarized in our current proposal) we have built on such findings to propose that there are in fact four distinct types of imagery, which rely on distinct neural systems. We expect individual differences in each type of imagery.

10. Kosslyn, S. M. and Thompson, W. L. (under review). When is early visual cortex activated during visual mental imagery? Theory and meta-analysis. *Psychological Review.*

This meta-analysis follows up the one reported by Kosslyn & Thompson (2000). This meta-analysis focuses on the question of when early visual cortex (Areas 17 or 18) is activated. This is important because such cortices are topographically organized; and thus activation in these areas is evidence that imagery involves depictive, nonlinguistic representations. Although most neuroimaging studies of visual mental imagery have revealed activation in early visual cortex (Area 17 or 18), many have not. This article uses a theory of visual mental imagery to produce a set of hypotheses that might explain the disparate results. A stepwise logistic multiple regression meta-analysis identified four variables that independently predict activation in early visual cortex: The sensitivity of the technique, whether details need to be inspected with high resolution, whether the eyes were open, and whether the task required judging spatial relations; the first three characteristics were associated with the presence of activation, and the last was associated with the absence of activation. These results lead us to make clear-cut predictions for future studies.

11. Dark/light studies

Our meta-analyses indicated that one variable that predicts whether primary visual cortex becomes activated during visual mental imagery is the level of ambient light in the room. The neuroimaging groups who find no activation in early visual areas during imagery always test their subjects in a totally darkened environment. It is possible that some ambient light is useful as a "catalyst" for visual imagery. The light coming through the eyelids (in the case of a study where subjects are asked to keep their eyes closed) may provide some

random activation, which would then be modulated by top-down processing. To investigate the possibility that the level of ambient light may influence facility with imagery, we have conducted a series of behavioral experiments with different levels of lighting. In one, we asked subjects to decide from memory whether uppercase letters of the alphabet have specific shape characteristics, such as curved lines (this is the same task used in Kosslyn et al., 1993, Experiment 3). We compared three conditions: When the subjects had their eyes open and looked at a blank white wall; eyes closed but with light on in the room; or eyes closed but also wearing a blindfold and with no light on in the room. And in fact, subjects made more errors and took more time in total darkness than when light was present, and had equivalent times and errors in both the eyes-open and eyes-closed-with-light conditions. However, this result only occurred when properties of shapes were queried. When spatial locations were evaluated (i.e., subjects decided whether a letter has a straight line that would fall along the side of an enclosing rectangle), now the results were exactly the opposite: The eyes-closed-in-darkness condition was best, resulting in faster response times and lower error rates. One interpretation of these results is that spatial properties are processed in an "object map" representation in the posterior parietal lobes, and in this case the activation in the visual buffer acts as a distraction.

To consider these findings in more detail, we conducted a very different additional study. We began by asking a group of subjects to verify 188 statements about properties of common objects, and to indicate whether they used imagery to make each judgment. On the bases of these ratings, we selected two groups of statements from the 80 that were rated most often as requiring imagery. One group (e.g., "The statue of liberty holds the torch in her right hand") described spatial relations, and one group (e.g., "A pig has a curly tail") described object properties. Half the statements of each type were true, and half were false. We divided each of these sets into two parts, and administered one part in darkness (when subjects also wore a blindfold) and the other part in full light (when subjects had their eyes closed). Each part was administered in each condition equally often over subjects, and each condition was administered in each order equally often. The results demonstrated that subjects could evaluate the spatial properties fastest, and made fewer errors, in total darkness, whereas for object statements, there was a trend for them to have a better performance when some ambient light filtered through.

We next considered the possibility that the key distinction was not object versus spatial properties, but rather another variable or variables confounded with these. Thus, we formulated six alternative hypotheses, each of which corresponded to a dimension along which the statements varied. We then asked another group of 16 subjects to rate each of the statements on each dimension. For example, whether the image had to be reorganized, whether it required focusing on specific details, or whether it was visually complex. We next computed a difference score for each statement by subtracting the mean response time in the darkness condition from that in the light condition; we also

computed the corresponding difference score for errors. These difference scores were then regressed onto the ratings. In a stepwise procedure, none of the alternative dimensions accounted for any significant variance in subjects' performance in evaluating the different items. Only the distinction between object versus spatial properties accounted for significant amounts of variance. In terms of our theory, if a task can be performed using the object map in the spatial-properties-processing system, the visual buffer need not be activated—and inhibiting such activation (by testing in total darkness) facilitated performance.

12. Kozhevnikov, M., & Kosslyn, S. M. (2000). Revising cognitive style dimension: Two orthogonal classes of visualizers (Paper presented at 41th Annual Meeting of the Psychonomic Society, New Orleans, November 16-19; a longer paper now being prepared for publication.)

Finally, this study focuses on the dorsal vs. ventral distinction in our theory (spatial vs. object process). In this study we propose and test a revision of the classic visualizer/verbalizer cognitive style dimension. Seventy subjects were administered a computerized battery of imagery tasks, standard paper-and-pencil spatial and verbal ability tests, and a visualizer-verbalizer cognitive style questionnaire. Two orthogonal groups of visualizers were identified. Whereas one group of visualizers (object imagers) scored lower than average on spatial imagery tasks (e.g., mental rotation), they scored higher than average on visual-object imagery tasks (e.g., degraded picture task). In contrast, the other group of visualizers (spatial imagers) scored higher than average on spatial imagery tasks (e.g., mental rotation), but performed significantly lower on visual imagery tasks. Response times of the object imagers were significantly faster in all types of tasks. The results provide evidence that dissociation between visual-object and visual-spatial imagery exists in individual differences in imagery and that the visualizer/verbalizer cognitive style is not a unitary construct, but involves two qualitatively different types of visualizers.